

# Hot Stars in Globular Clusters – A Spectroscopist’s View

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## ABSTRACT

Globular clusters are ideal laboratories to study the evolution of low-mass stars. In this work we concentrate on three types of hot stars observed in globular clusters: horizontal branch stars, UV bright stars, and white dwarfs. After providing some historical background and information on gaps and blue tails we discuss extensively hot horizontal branch stars in metal-poor globular clusters, esp. their abundance anomalies and the consequences for the determination of their atmospheric parameters and evolutionary status. Hot horizontal branch stars in metal-rich globular clusters are found to form a small, but rather inhomogeneous group that cannot be explained by *one* evolutionary scenario. Hot UV bright stars show a lack of classic post-AGB stars that may explain the lack of planetary nebulae in globular clusters. Finally we discuss first results of spectroscopic observations of white dwarfs in globular clusters.

*Subject headings:* (Galaxy:) globular clusters: general – stars: horizontal-branch – stars: post-AGB – (stars:) white dwarfs

## 1. Historical Background

Globular clusters are the closest approximation to a physicist’s laboratory in astronomy. They are densely packed, gravitationally bound systems of several thousands to about one million stars. The dimensions of the globular clusters are small compared to their distance from us: half of the light is generally emitted within a radius of less than 10 pc, whereas the closest globular cluster has a distance of 2 kpc and 90% lie more than 5 kpc away. We can thus safely assume that all stars within a globular cluster lie at the same distance from us. With ages in the order of  $10^{10}$  years globular clusters are among the oldest objects in our Galaxy. Contrary to the field of the Galaxy globular clusters formed stars only once in the beginning. Because the duration of that star formation episode is short compared to the current age of the globular clusters the stars within one globular cluster are essentially coeval. In addition all stars within one globular cluster (with few exceptions) show the same initial abundance pattern (which may differ from one cluster to another).

As we know today that Galactic globular clus-

ters are old stellar systems people are often surprised by the presence of hot stars in these clusters since hot stars are usually associated with young stellar systems. The following paragraphs will show that hot stars have been known to exist in globular clusters for quite some time:

About a century ago Barnard (1900) reported the detection of stars in globular clusters that were much brighter on (blue-sensitive) photographic plates than they appeared visually: *“Of course the simple explanation of this peculiarity is that these stars, so bright photographically and so faint visually, are shining with a much bluer light than the stars which make up the main body of the clusters.”*

In 1915 Shapley started a project to obtain colours and magnitudes of individual stars in globular and open clusters (Shapley 1915a). In the first globular cluster (M 3, Shapley 1915b) he found a double peaked distribution of colours, with a red maximum and a blue secondary peak. He noticed that – in contrast to what was known for field dwarf (i.e. main sequence) stars – the stars in M 3 became bluer as they became fainter.

ten Bruggencate (1927, p. 130) used Shapley’s data on M 3 and other clusters to plot magnitude versus colour (replacing luminosity and spectral type in the Hertzsprung-Russell diagram) and thus produced the first colour-magnitude diagrams<sup>1</sup> (“FARBENHELLIGKEITSDIAGRAMME”). In these colour-magnitude diagrams (CMD’s) ten Bruggencate noted the presence of a red giant branch that became bluer towards fainter magnitudes, in agreement with Shapley (1915b). In addition, however, he saw a horizontal branch (“HORIZONTALER AST”) that parted from the red giant branch and extended far to the blue at constant brightness. Greenstein (1939) observed a colour-magnitude diagram for M 4 and noticed that – while hot main-sequence stars were completely missing – there existed a group of bright stars above the horizontal branch and on the blue side of the red giant branch. Similar stars appeared also in the CMD’s presented by Arp (1955).

As more CMD’s of globular clusters were obtained it became obvious that the horizontal branch morphology varied quite considerably between individual clusters. The clusters observed by Arp (1955) exhibited extensions of the blue horizontal branch towards bluer colours and fainter visual magnitudes, i.e. towards hotter temperatures<sup>2</sup> (see Fig. 1). In some of Arp’s CMD’s (e.g. M 15, M 2) these **blue tails** show gaps at varying brightness (see Sect. 2.1 for details).

About 25 years after their discovery first ideas about the nature of the horizontal branch stars began to emerge: Hoyle & Schwarzschild (1955) were the first to identify the horizontal branch stars with post-red giant branch stars that burn helium in the central regions of their cores.

Sandage & Wallerstein (1960) noted a correlation between the metal abundance and the horizontal branch morphology seen in globular cluster CMD’s: the horizontal branch (HB) became bluer

with decreasing metallicity. Faulkner (1966) managed for the first time to compute zero age horizontal branch (ZAHB) models that qualitatively reproduced this trend of HB morphology with metallicity without taking into account any mass loss but assuming a rather high helium abundance of  $Y = 0.35$ . Iben & Rood (1970), however, found that *“In fact for the values of  $Y$  and  $Z$  most favored ( $Y \geq 0.25 \rightarrow 0.28$ ,  $Z = 10^{-3} \rightarrow 10^{-4}$ ), individual tracks are the stubbiest. We can account for the observed spread in color along the horizontal branch by accepting that there is also a spread in stellar mass along this branch, bluer stars being less massive (on the average) and less luminous than redder stars.”*

Comparing HB models to observed globular cluster CMD’s Rood (1973) found that an HB that *“...is made up of stars with the same core mass and slightly varying total mass, produces theoretical c-m diagrams very similar to those observed. ...A mass loss of perhaps  $0.2 M_{\odot}$  with a random dispersion of several hundredths of a solar mass is required somewhere along the giant branch.”* The assumption of mass loss on the red giant branch diminished the need for very high helium abundances.

While Sweigart & Gross (1974, 1976) showed that HB tracks including semi-convection covered a larger temperature range, Sweigart (1987) noted that even with semi-convection a spread in mass was still necessary to explain the observations.

Caloi (1972) investigated the ZAHB locations of stars with very low envelope masses ( $\leq 0.02 M_{\odot}$ ) that lie along the extended or **extreme HB** (= EHB) at high effective temperatures ( $> 20,000$  K) and found that they can be identified with the subdwarf B stars known in the field (Greenstein 1971). Sweigart et al. (1974) and Gingold (1976) studied the post-HB evolution and found that – in contrast to the more massive blue HB stars – EHB models do not ascend the second (asymptotic) giant branch (AGB), but evolve directly to the white dwarf domain.

Thus our current understanding sees **horizontal branch stars** as stars that burn helium in a core of about  $0.5 M_{\odot}$  and hydrogen in a shell. The more massive the hydrogen envelope is the cooler is the resulting star. The masses of the hydrogen envelopes vary from  $0.02 M_{\odot}$  to more than  $0.2 M_{\odot}$

<sup>1</sup>Shapley (1930, p.26, footnote) disliked the idea of plotting individual data points – he thought that the small number of measurements might lead to spurious results.

<sup>2</sup>The change in slope of the horizontal branch towards higher temperatures is caused by the decreasing sensitivity of  $B - V$  to temperature on one hand and by the increasing bolometric correction for hotter stars (i.e. the maximum of stellar flux is radiated at ever shorter wavelengths for increasing temperatures, making stars fainter at  $V$ ) on the other hand.

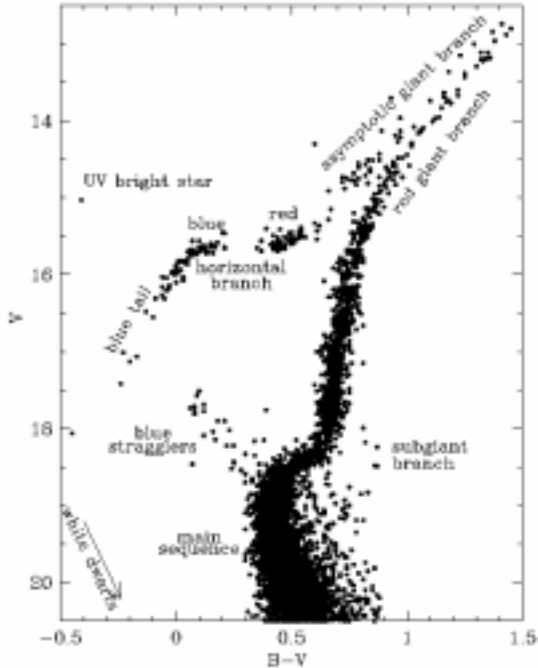


Fig. 1.— Colour-magnitude diagram of M 3 (Buonanno et al. 1994) with the names of the principal sequences.

for metal-poor hot HB stars<sup>3</sup>. Hot HB stars eventually evolve up the asymptotic giant branch. The less-massive envelopes of the even hotter EHB stars ( $M_{\text{env}} \leq 0.02 M_{\odot}$ ,  $T_{\text{eff}} > 20,000$  K) do not support hydrogen shell burning and EHB stars do not climb the AGB, but evolve directly to the white dwarf domain and are thus also called AGB manqué stars (Greggio & Renzini 1990). For a review on HB evolution see Sweigart (1994). In the CMD hot horizontal branch stars populate the blue horizontal branch and the brighter part of the blue tail. The transition from hot to extreme HB stars takes place towards the fainter part of the blue tail at  $M_V \gtrsim 3^m$ .

But hot horizontal branch stars are neither the brightest nor the bluest stars in globular clusters: Already Shapley (1930, p. 30) remarked

<sup>3</sup>Due to the higher opacities in their envelopes metal-rich HB stars are cooler than metal-poor ones with the same envelope mass. Therefore hot metal-rich HB stars must have less massive envelopes than metal-poor ones, reducing the upper limit to, e.g.,  $\approx 0.15 M_{\odot}$  for solar-metallicity hot HB stars

that “Occasionally, there are abnormally bright blue stars, as in Messier 13, but even these are faint absolutely, compared with some of the galactic B stars”. This statement refers to stars like those mentioned by Barnard (1900) which in colour-magnitude diagrams lie above the horizontal branch and blueward of the red giant branch (see Fig. 1). This is also the region where one would expect to find central stars of planetary nebulae, which are, however, rare in globular clusters: Until recently (Jacoby et al. 1997) Ps1 (Pease 1928), the planetary nebula in M 15 with its central star K 648, and IRAS18333-2357 in M 22 (Cohen & Gillett 1989) remained the only such objects known in globular clusters (see also Sect. 4).

Apart from analyses of individual stars like vZ 1128 in M 3 (Strom & Strom 1970, and references therein) and Barnard 29 in M 13 (Traving 1962; Stoeckley & Greenstein 1968) the first systematic work on these bright blue stars was done by Strom et al. (1970). All stars analysed there show close to solar helium content, contrary to the hot and extreme horizontal branch stars, which in general are depleted in helium (Heber 1987; Moehler et al. 2000b, see also Sect. 2). Strom et al. identified the brightest and bluest UV bright stars with models of post-AGB stars (confirming the ideas of Schwarzschild & Härm 1970) and the remaining ones with stars evolving from the horizontal branch towards the AGB. This means that all of the stars in their study are in the double-shell burning stage. Zinn et al. (1972) performed a systematic search for such stars using the fact that they are brighter in the U band than all other cluster stars. This also resulted in the name **UV Bright Stars** for stars brighter than the horizontal branch and bluer than the red giant branch<sup>4</sup>.

Most of the UV bright stars found in ground based searches are cooler than 30,000 K, although theory predicts stars with temperatures up to 100,000 K (e.g., Schönberner 1983; Renzini 1985). The ground based searches, however, are biased towards cooler stars due to the large bolometric corrections for hotter stars<sup>4</sup>. It is therefore not

<sup>4</sup>As the flux maximum moves to ever shorter wavelengths for increasing temperatures, hot UV bright stars may be rather faint not only in V, but also in the U band (see also Sect. 4). Thus UV bright stars will appear brighter than the HB and bluer than the red giant branch only if they are cool and/or luminous.

surprising that space based searches in the vacuum UV (Ultraviolet Imaging Telescope, Stecher et al. 1997) discovered a considerable number of additional *hot* UV bright stars in a number of globular clusters (see also Sect. 4).

Space based observatories also contributed a lot of other information about hot stars in globular clusters: Observations with the Ultraviolet Imaging Telescope (UIT) showed the unexpected presence of blue HB stars in metal-rich globular clusters like NGC 362 (Dorman et al. 1997) and 47 Tuc (O’Connell et al. 1997). At about the same time Hubble Space Telescope (HST) observations of the core regions of globular clusters showed long blue tails in metal-rich bulge globular clusters (Rich et al. 1997). These metal-rich globular clusters are discussed in more detail in Sect. 3. The interest in hot old stars like horizontal branch and UV bright stars has been revived and extended by the discovery of the UV excess in elliptical galaxies (Code & Welch 1979; de Boer 1982) for which they are the most likely sources (Greggio & Renzini 1990, 1999; Dorman et al. 1995; Dorman 1997; Brown et al. 1997, see also Sects. 3 and 4).

The most recent addition to the family of hot stars in globular clusters are the white dwarfs found in HST observations of M 4 (Richer et al. 1995, 1997), NGC 6752 (Renzini et al. 1996), NGC 6397 (Paresce et al. 1995; Cool et al. 1996), and 47 Tuc (Zoccali et al. 2001), which are discussed in Sect. 5.

## 2. Horizontal Branch Stars in Metal-Poor Globular Clusters

### 2.1. Gaps and Blue Tails

As mentioned in Sect. 1 the more vertical extensions of the blue HB (blue tails, cf. Fig. 1) seen in the colour-magnitude diagrams (CMD’s) of many globular clusters often display gaps at varying brightness. Such gaps are also known for field HB stars (Newell 1973; Heber et al. 1984). For a list of globular clusters with blue tails see Fusi Pecci et al. (1993). Catelan et al. (1998) and Ferraro et al. (1998) give comprehensive lists of clusters that show gaps and/or bimodal horizon-

tal branches<sup>5</sup>. Ferraro et al. (1998) argue that all intermediate metallicity globular clusters ( $[\text{Fe}/\text{H}] \approx -1.5$ ) with a very long blue tail show a gap at about 18,000 K. Piotto et al. (1999) extend the discussion to include metal-rich globular clusters and argue for a gap at *constant mass*, which – for differing metallicities – will result in gaps at different temperatures. In the following discussion we will refer to the stars along the vertical extensions of the blue HB simply as blue tail (BT) stars and the stars along the horizontal part of the HB (bluer than the RR Lyrae gap) will be called blue HB (BHB) stars. Calling the stars along the vertical extension of the blue HB subdwarf B stars<sup>6</sup> (e.g., Baily et al. 1992) or extreme HB stars (i.e. stars with so little hydrogen envelope that they do not burn hydrogen in a shell) makes implicit assumptions about their physical nature and evolutionary status that are in most cases not correct (a point very well illustrated in Fig. 8 of Testa et al. 2001).

As the gaps are not expected from canonical evolutionary scenarios various non-canonical explanations have been suggested during the past 25 years and some of them are given below (more detailed descriptions of possible explanations for the gaps can be found in Crocker et al. 1988; Catelan et al. 1998; Ferraro et al. 1998).

#### *Diverging evolutionary paths*

The evolution away from the zero-age HB (ZAHB) could in principle transform a uniformly populated ZAHB into a bimodal HB as stars evolve. Newell (1973) was the first to suggest this explanation for the gap seen in *UBV* photometry of field horizontal branch stars at temperatures corresponding to  $\approx 12,900$  K. Heber et al. (1984) suggested that the small gap at  $\approx 20,000$  K between field HBB (=horizontal branch B type) and sdB stars could be explained by diverging evolution.

Support for this idea came from Lee et al. (1994), but other calculations show that the effect is not large enough to explain the gaps along the horizontal branches (see, e.g., Dorman et al.

<sup>5</sup>In recent deep colour-magnitude diagrams a group of very faint blue stars ( $M_V \geq 4^m5$ ) shows up in some globular clusters, e.g. NGC 2808 (Sosin et al. 1997; Walker 1999; Bedin et al. 2000),  $\omega$  Cen (Whitney et al. 1998; D’Cruz et al. 2000).

<sup>6</sup>For analyses of field subdwarf B (sdB) stars see Heber (1986); Moehler et al. (1990b); Saffer et al. (1994, 1997)

1991; Catelan et al. 1998).

#### *Mass loss*

D’Cruz et al. (1996) found that bimodal horizontal branches become more probable for increasing metallicity because the range in mass loss efficiency required to produce an EHB star stays constant (i.e. independent of metallicity), whereas only a very narrow range of mass loss efficiency can produce hot HB stars at high metallicities. Thus the number of hot HB stars is expected to decrease with increasing metallicity, opening a wide gap between cool HB stars and EHB stars at high metallicity. Yong et al. (2000) find that mass loss on the horizontal branch could produce extreme HB stars (like the sdB’s) in very metal-rich environments like the open cluster NGC 6791 ( $[\text{Fe}/\text{H}] = +0.5$ ). While these scenarios offer good explanations for the sdB stars and the large gap discovered in the metal-rich open cluster NGC 6791 (Kaluzny & Udalski 1992; Liebert et al. 1994) it cannot explain the smaller gaps seen in the mostly rather metal-poor globular clusters. Rood et al. (1997) and Ferraro et al. (1998) also discuss variations in mass loss on the red giant branch as possible causes for gaps along the HB. Caloi (1999), however, argues that HB evolution would tend to fill in gaps in the initial ZAHB distribution if the RGB mass loss was actually able to produce them.

#### *Differences in, e.g., $[\text{CNO}/\text{Fe}]$ , rotation etc.*

Rood & Crocker (1989) suggest differences in CNO or He abundances or rotation rates as possible causes for the gaps. For hot HB stars a decrease in *CNO abundances* results in bluer colours at a given envelope mass (a similar effect as seen for a decrease in overall metallicity). Increasing the *He abundance* in the hydrogen envelope of a hot HB star will increase the energy production in the H-burning shell, thereby resulting in brighter horizontal branch stars (for more details see Sweigart 1997b). *Rotation* would delay the helium core flash in a red giant thereby leading to an increase in the helium core mass and more mass loss, resulting in bluer and brighter HB stars (see also Buonanno et al. 1985; Peterson et al. 1995; Sills & Pinsonneault 2000, for a discussion of rotation and blue tails). Bimodal distributions in any of these parameters may thus create gaps along the horizontal branch.

#### *Dynamical interactions*

A gap would be easy to understand if the stars

above and below the gap were created by different mechanisms: If the stars below the gaps do not descend from red giants there is no reason why they should form a smooth extension of the sequence defined by red giants descendants. The most prominent candidates for such different formation mechanisms are binary interactions like common envelope evolution, merging of stars, etc. (for more details see Bailyn et al. 1992; Bailyn 1995; Moehler et al. 1997b).

Such binary scenarios create stars that resemble the sdB, sdOB, and sdO stars known from the field of the Milky Way, but not hot HB stars. The main objection to the dynamical scenarios is that in this case the relative numbers of red giant (RGB/AGB) to “true” HB stars, which gives an estimate of the cluster’s original helium abundance, would vary between clusters and pretend varying primordial helium abundances (see Buonanno et al. 1985; Fusi Pecci et al. 1993). Another objection is the tight sequence in temperature and surface gravity reported by Heber et al. (1986) and Moehler et al. (1997b) for stars below the faint gap in NGC 6752. Crocker et al. (1988) cite the similar blue tails in M 15 and NGC 288, which are dynamically very different, as argument against the production of blue tail stars by dynamical interactions like merging. Ferraro et al. (1997) argue in the same way with respect to M 13 and M 3, which are dynamically very similar but have very different HB morphologies. Bedin et al. (2000, NGC 2808) and D’Cruz et al. (2000,  $\omega$  Cen) find no radial gradient in the number of very faint blue stars<sup>5</sup> to blue HB stars, arguing against dynamical interactions as cause for the extremely faint blue stars. Testa et al. (2001) on the other hand find the most pronounced blue tail in the most metal-rich, but also densest globular cluster of their sample, NGC 6626, which also shows indications for a higher than usual helium content. See Buonanno et al. (1997) for a detailed discussion of the relation between cluster density and the presence of blue tails.

Soker (1998) suggests that the interaction of red giants with close-in planets will spin-up the red giant, thereby increasing its mass loss and the temperature of the resulting HB star. The different fates of a planet inside an extended stellar envelope could then result in multimodal HB morphologies. So far, only 47 Tuc has been searched

for planets, with negative results (Gilliland et al. 2000).

#### *Atmospheric processes*

Caloi (1999) proposed the change from convection to diffusion in the stellar atmospheres as an explanation for the gaps around  $(B - V)_0 = 0$ . This scenario would predict chemical peculiarities in bluer stars. Grundahl et al. (1999) suggest radiative levitation of heavy elements in the atmosphere as cause for the  $u$ -jump observed in many globular clusters – a claim which is supported by the calculations of Hui-Bon-Hoa et al. (2000). A more detailed discussion of the rôle of diffusion in hot HB stars can be found in Sect. 2.4.

#### *Helium mixing*

Helium mixing in red giants means mixing deep enough to enrich the red giant’s envelope with helium freshly produced in the hydrogen burning shell. A red giant experiencing helium mixing will evolve to higher luminosities, thereby losing more mass than canonically expected and producing a hotter HB star. The helium enrichment of the hydrogen envelope increases the efficiency of the hydrogen shell burning and thus the luminosity of the HB star (see Sweigart 1997a,b, for more details). Different amounts of mixing in the red giant precursors could thus produce HB stars in different temperature regimes and at the same time explain some of the puzzling abundance distributions found in globular cluster red giants (see Kraft 1994; Kraft et al. 1997, for reviews, but also Gratton et al. (2001) for most recent evidence of primordial abundance variations). Charbonnel et al. (2000) and Caloi (2001), however, argue that current observational results both for HB stars and red giants do not support the idea of helium mixing being active in globular cluster red giants.

#### *Statistical fluctuations*

Catelan et al. (1998) used numerous synthetic HB simulations to show quite convincingly that at least some of the gaps may be due to statistical fluctuations. Ferraro et al. (1998) and Piotto et al. (1999), however, report gaps at physically similar positions (i.e. temperature or mass) in several globular clusters, arguing against statistical fluctuations.

## **2.2. Atmospheric parameters ( $T_{\text{eff}}$ , $\log g$ )**

Already early studies of hot HB stars in globular clusters showed discrepancies between observational results and theoretical expectations:

Graham & Doremus (1966) mentioned that the comparison of  $(c_1)_0$  vs.  $(b - y)_0$  for 50 blue HB stars in NGC 6397 to models from Mihalas (1966) indicated low surface gravities and a mean mass of  $0.3 M_\odot$  ( $0.4 M_\odot$ ) for solar (negligible) helium abundance, assuming  $(m - M)_0 = 12^m0$  and  $E_{B-V} = 0^m16$ . *“It is clear that the accurate fixing of this parameter  $[\log g]$  is of the greatest importance for fixing limits to the masses of the horizontal branch stars since there seems no other way, at present, of determining them more directly.”* Later spectroscopic analyses of HB stars (see cited papers for details) in globular clusters with and without gaps along their horizontal branches and/or blue tails reproduced this effect (cf. Fig. 2): Crocker et al. (1988) deal with five globular clusters, namely M 3, M 5, M 15, M 92, and NGC 288 (of which M 5 does not show any gap along the BHB/BT). de Boer et al. (1995) analysed BHB stars in NGC 6397, which shows a short, horizontal blue HB. Moehler et al. (1995, 1997a) study blue tail stars in M 15. Heber et al. (1986) and Moehler et al. (1997b) analyse blue tail stars in NGC 6752 which is well known for its extremely long blue tail.

The zero-age HB (ZAHB) in Fig. 2 marks the position where the HB stars have settled down and started to quietly burn helium in their cores. The terminal-age HB (TAHB) is defined by helium exhaustion in the core of the HB star ( $Y_C < 0.0001$ ). In order to allow a better search for any common physical gaps the stars are marked by their position relative to gaps along the HB: M 92, M 15, M 3, and NGC 288 show a gap at  $M_V \approx 0^m6$  to  $1^m4$  (bright gap). Stars above that bright gap are marked by filled circles, stars below by open circles. M 15 and NGC 6752 show a faint gap (or underpopulated region) at  $M_V \approx 3^m$ . Stars below these faint gaps are marked by filled triangles. NGC 6397 and M 5 show no obvious gaps (three-pointed symbols). Fig. 2 shows that the faint gap separates hot HB from EHB stars at about 20,500 K, which is somewhat hotter than the “temperature” gap for intermediate metallicity clusters at 18,000 K suggested by Ferraro et

al. (1998) and could correspond to the “forbidden mass” region discussed by Piotto et al. (1999). The bright gap roughly corresponds to the underpopulated region at  $T_{\text{eff}} \approx 10,000$  K to 12,600 K (long-dashed line), although the distinction between stars above and below the bright gap is not as clear as for the faint gap. The blue tail stars below the bright gap (and above the faint gap) are hot HB stars and *not* hot subdwarfs like the field sdB stars. For temperatures between 11,500 K and 20,500 K the observed positions in the ( $\log g$ ,  $T_{\text{eff}}$ )-diagram fall mostly above the ZAHB and in some cases even above the TAHB<sup>7</sup>. This agrees with the finding of Saffer et al. (1997) that field HBB stars show a larger scatter away from the ZAHB in  $T_{\text{eff}}$ ,  $\log g$  than sdB stars.

Knowing the atmospheric parameters of the stars and the distances to the globular clusters allows to determine masses for the stars (cf. Moehler et al. 1994, 1995, 1997b; de Boer et al. 1995). While the stars in M 3, M 5, and NGC 6752 have mean masses consistent with the canonical values, the hot HB stars in all other clusters show masses that are significantly lower than predicted by canonical HB evolution – even for temperatures cooler than 11,500 K where the stars don’t deviate from the canonical tracks in surface gravity. Scenarios like the merging of two helium-core white dwarfs (Iben & Tutukov 1984) or the stripping of red giant cores (Iben & Tutukov 1993; Tuchman 1985) produce low-mass stars that are either too hot (merger) or too short-lived (stripped core) to explain the low-mass HB stars.

Also some UV observations suggest discrepancies between theoretical expectations and observational results: The IUE (International Ultraviolet Explorer) and HUT (Hopkins Ultraviolet Telescope) spectra of M 79 (Altner & Matilsky 1993; Dixon et al. 1996) suggest lower than expected gravities and higher than expected metallicities for hot HB stars (but see Vink et al. 1999, who do not need low surface gravities to fit the HUT data). Hill et al. (1996) find from UIT photometry of M 79 that stars bluer than  $m_{152} - m_{249} = -0^m.2$

<sup>7</sup>Crocker (1991) finds from the analysis of spectra for BHB stars in M 3 and M 13 that the M 3 stars cooler than 11,200 K stay very close to the ZAHB (the one star at  $T_{\text{eff}} \approx 12,500$  K shows lower  $\log g$ ). The M 13 stars cooler than 11,200 K stay mostly close to the ZAHB, but the majority of stars in that cluster is hotter and shows lower  $\log g$ .

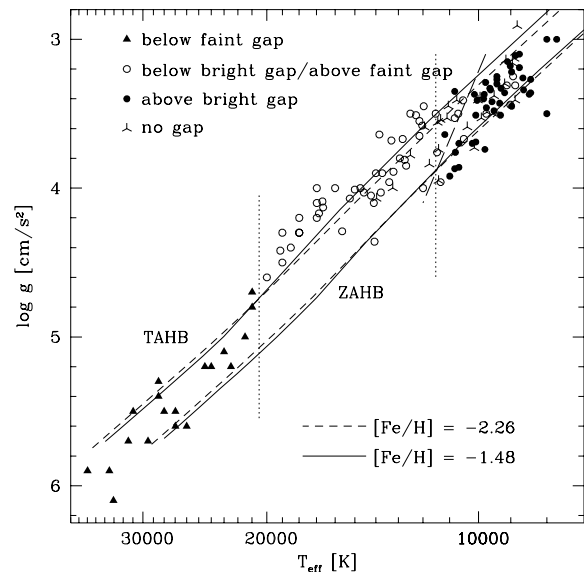


Fig. 2.— The results of Crocker et al. (1988, M 3, M 5, M 92, NGC 288), de Boer et al. (1995, NGC 6397), Moehler et al. (1995, 1997a, M 15), Moehler et al. (1997b, NGC 6752) compared to evolutionary tracks from Dorman et al. (1993). ZAHB and TAHB stand for zero-age and terminal-age HB (see text for details). The long-dashed line marks the possible low-temperature gap. The dotted lines mark the regions of low  $\log g$  (see text for details).

lie above the ZAHB, whereas cooler stars scatter around the ZAHB. Parise et al. (1998, UIT data of M 13) find a lack of stars close to the ZAHB at a colour (temperature) range similar to the low  $\log g$  range shown in Fig. 2. Whitney et al. (1998) claim from UIT observations that the bluest HB stars in  $\omega$  Cen have lower than expected luminosities and that a considerable number of stars lie below the ZAHB. This is confirmed by HST observations of D’Cruz et al. (2000) who find a “blue hook” feature at the extremely hot end of the blue tail in  $\omega$  Cen and also several sub-ZAHB stars. These “blue hook” stars could be similar to the helium-rich sdB found in M 15 (Moehler et al. 1997a). Landsman et al. (1996) on the other hand find good agreement between UIT photometry of blue stars in NGC 6752 and a standard ZAHB (in position and HB luminosity width) for  $(m - M)_0 = 13^m.05$  and  $E_{B-V} = 0^m.05$ .

So far we discussed results from low to medium resolution spectra. High resolution spectra offer further insights into the nature of hot HB stars, esp. their abundances and rotational velocities, which are discussed in the next two sections. We'll come back to the problems described here in Sect. 2.5.

### 2.3. Rotational velocities

Peterson (1983, 1985a,b) found from high-resolution spectroscopic studies of blue HB stars in M 3, M 4, M 5, M 13, and NGC 288 that clusters with bluer HB morphologies show higher rotation velocities among their HB stars, which supports the idea that rotation affects the distribution of stars along the HB. However, the analysis of Peterson et al. (1995) shows that while the stars in M 13 (which has a long blue tail) rotate on average faster than those in M 3 (which has only a short blue HB), the stars in NGC 288 and M 13 show *slower* rotation velocities at *higher* temperatures. These results are consistent with those reported for blue HB and blue tail stars in M 13 by Behr et al. (2000a), who determined rotational velocities for stars as hot as 19,000 K (considerably hotter than the stars analysed by Peterson et al. 1995). They found that stars hotter than about 11,000 K have significantly lower rotational velocities than cooler stars and that the change in mean rotational velocity may coincide with the gap seen along the blue HB of M 13. Also the results of Cohen & McCarthy (1997, M 92) and Behr et al. (2000b, M15) show that HB stars cooler than  $\approx 11,000$  K to 12,000 K in general rotate faster than hotter stars.

Sills & Pinsonneault (2000) study theoretical models for the rotation of HB stars and find that the observed rotation of cool BHB stars in M 13 can be explained if the RGB stars have rapidly rotating cores and differential rotation in their convective envelopes and if angular momentum is redistributed from the rapidly rotating core to the envelope (most likely on the horizontal branch). If, however, turn-off stars rotate with less than 4 km/s, a rapidly rotating core in the main-sequence stars (violating helioseismological results for the Sun) or an additional source of angular momentum on the RGB (e.g. mass transfer in close binaries or due to planets as described by Soker & Harpaz 2000) are required to explain the rotation

of BHB stars. The change in rotation rates towards higher temperatures is not predicted by the models but could be understood as a result of gravitational settling, which creates a mean molecular weight gradient, that then inhibits angular momentum transport in the star. Sweigart (2001) suggests that the weak stellar wind invoked to reconcile observed abundances in hot and extreme HB stars with diffusion calculations (cf. Sect. 2.4) could also carry away angular momentum from the surface layers and thus reduce the rotational velocities of these stars.

Soker & Harpaz (2000) argue that the distribution of rotational velocities along the HB can be explained by spin-up of the progenitors due to interaction with low-mass companions, predominantly gas-giant planets, in some cases also brown dwarfs or low-mass main-sequence stars (esp. for the very hot extreme HB stars). The slower rotation of the hotter stars in their scenario is explained by mass loss *on* the HB, which is accompanied by efficient angular momentum loss. This scenario, however, does not explain the sudden change in rotational velocities and the coincidence of this change with the onset of radiative levitation.

### 2.4. Atmospheric abundances

It has been realized early on that the blue HB and blue tail stars in globular clusters show weaker helium lines than field main sequence B stars of similar temperatures: Searle & Rodgers (1966, NGC 6397); Greenstein & Münch (1966, M 5, M 13, M 92); Sargent (1967, M 13, M 15, M 92). Greenstein et al. (1967) already suggested diffusion to explain this He deficiency.

Michaud et al. (1983) performed the first theoretical study of diffusion effects in hot and extreme horizontal branch stars. Using the evolutionary tracks of Sweigart & Gross (1976) they found for the metal-poor models that *“in most of each envelope, the radiative acceleration on all elements (i.e. C, N, O, Ca, Fe) is much larger than gravity which is not the case in main-sequence stars.”* The elements are thus pushed towards the surface of the star. Turbulence affects the different elements to varying extent, but generally reduces



the overabundances<sup>8</sup>. Models without turbulence and/or mass loss (which may reduce the effects of diffusion) predict stronger He depletions than are observed. A weak stellar wind could alleviate this discrepancy (Heber 1986; Michaud et al. 1989; Fontaine & Chayer 1997; Unglaub & Bues 1998, discuss this effect, albeit for hotter stars).

The extent of the predicted abundance variations varies with effective temperature, from none for HB stars cooler than about  $5800 \pm 500$  K (due to the very long diffusion timescales) to 2 – 4 dex in the hotter stars (the hottest model has  $T_{\text{eff}} = 20,700$  K) and also depends on the element considered. The overabundances in the two hottest models (12,500 K and 20,700 K) are limited to 3 dex for relatively abundant elements by the saturation of lines. Less abundant elements like P, Eu, Ga could show much larger overabundances before their lines saturate (up to 5 dex for original values of  $[M/H] = -2$ ).

Observations of BHB and BT stars in globular clusters support the idea of diffusion being active above a certain temperature:

Abundance analyses of blue HB stars cooler than 11,000 K to 12,000 K in general show no deviations from the globular cluster abundances derived from red giants: Glaspey et al. (1986, NGC 6397), Glaspey et al. (1989, NGC 6752), Lambert et al. (1992, M 4, NGC 6397), Cohen & McCarthy (1997, M 92) Behr et al. (1999, M 13), Behr et al. (2000b, M 15), Peterson et al. (2000, NGC 6752). For stars hotter than 11,000 K to 12,000 K, however, departures from the general globular cluster abundances are found, e.g. iron enrichment to solar or even super-solar values and strong helium depletion: Glaspey et al. (1989, NGC 6752), Behr et al. (1999, M 13), Peterson et al. (1995, NGC 288, M 13), Moehler et al. (2000b, NGC 6752), Behr et al. (2000b, M 15), Peterson et al. (2000, NGC 6752). This agrees with the finding of Altnier & Matilsky (1993) and Vink et al. (1999) that solar metallicity model atmospheres are required to fit the UV spectra of M 79.

<sup>8</sup>Michaud (1982) and Charbonneau & Michaud (1988) showed that meridional circulation can prevent gravitational settling and that the limiting rotational velocity decreases with decreasing  $\log g$ . Behr et al. (2000b) note that two of the HB stars hotter than 10,000 K show higher rotational velocities and much smaller abundance deviations.

All this evidence supports the recent suggestion of Grundahl et al. (1999) that the onset of diffusion in stellar atmospheres may play a rôle in explaining the jump along the HB towards brighter  $u$  magnitudes at effective temperatures of about 11,500 K. This jump in  $u, u-y$  is seen in all CMD's of globular clusters that have Strömgren photometry of sufficient quality<sup>9</sup>. The observed HB stars return to the theoretical ZAHB at temperatures between 15,000 K and 20,000 K (Grundahl et al. 1999, Fig. 1). The effective temperature of the jump is roughly the same for all clusters, irrespective of metallicity, central density, concentration or mixing evidence, and coincides with the apparent gap in  $T_{\text{eff}}, \log g$  seen in Fig. 2 at  $T_{\text{eff}} \approx 10,000$  K to 12,000 K. This coincides with the region where surface convection zones due to hydrogen and He I ionization disappear in HB stars (Sweigart 2001).

Radiative levitation of heavy elements decreases the far-UV flux and by backwarming increases the flux in  $u$ . Grundahl et al. (1999) show that the use of metal-rich atmospheres ( $[Fe/H] = +0.5$  for scaled-solar ATLAS9 Kurucz model atmospheres with  $\log \epsilon_{Fe, \odot} = 7.60$ ) improves the agreement between observed data and theoretical ZAHB in the  $u, u-y$ -CMD at effective temperatures between 11,500 K and 20,000 K, but it worsens the agreement between theory and observation for hotter stars in the Strömgren CMD of NGC 6752 (see their Fig. 8). Thus diffusion may either not be as important in the hotter stars or the effects may be diminished by a weak stellar wind.

The gap at  $(B-V)_0 \approx 0$  discussed by Caloi (1999, see Sect. 2.1) is not directly related to the  $u$ -jump as it corresponds to an effective temperature of about 9000 K and is also not seen in every cluster (which would be expected if it were due to an atmospheric phenomenon). The gap at  $T_{\text{eff}} \approx 13,000$  K seen in the  $c_1, b-y$  diagram of field horizontal branch stars (Newell 1973; Newell & Graham 1976) may be related to the  $u$ -jump as the  $c_1$  index contains  $u$ .

The abundance distribution within a stellar atmosphere influences the temperature stratification

<sup>9</sup>Bedin et al. (2000) report a  $U$  jump for NGC 2808 and Markov et al. (2001) detect it in their  $UBV$  photometry of M 5.

and thereby the line profiles and the flux distribution of the emergent spectrum. A deviation in atmospheric abundances of HB stars from the cluster metallicity due to diffusion would thus affect their line profiles and flux distribution. Model atmospheres calculated for the cluster metallicity may then yield wrong results for effective temperatures and surface gravities when compared to observed spectra of HB stars. Self-consistent model atmospheres taking into account the effects of gravitational settling and radiative levitation are, however, quite costly in CPU time and have started to appear only quite recently for hot stars (Dreizler & Wolff 1999; Hui-Bon-Hoa et al. 2000).

## 2.5. Atmospheric parameter revisited

Analysis of a larger sample of hot and extreme HB stars in NGC 6752 (Moehler et al. 2000b) showed that the use of model atmospheres with solar or super-solar abundances removes much of the deviation from canonical tracks both in  $T_{\text{eff}}$ ,  $\log g$  and  $T_{\text{eff}}$ , mass for hot HB stars discussed in Sect. 2.2. However, some discrepancies remain, indicating that the low  $\log g$ , low mass problem cannot be completely solved by scaled-solar metal-rich atmospheres (which *do* reproduce the *u*-jump reported by Grundahl et al. 1999). As Michaud et al. (1983) noted diffusion will not necessarily enhance all heavy elements by the same amount and the effects of diffusion vary with effective temperature. Elements that were originally very rare may be enhanced even stronger than iron (see also Behr et al. 1999, where P and Cr are enhanced to supersolar abundances). The question of whether diffusion is the (one and only) solution to the “low gravity” problem cannot be answered without detailed abundance analyses to determine the actual abundances and model atmospheres that allow to use non-scaled solar abundances (like ATLAS12 Kurucz 1992).

## 2.6. Where do we stand?

The spectroscopic analyses of BHB and blue tail stars in globular clusters suggest that the faint gap or underpopulated region at  $M_V \approx 3^m$  can be identified with the transition from hot to extreme HB stars, while the bright gap is probably caused by the onset of radiative levitation in the atmospheres of the hot HB stars. While the sudden change in rotational velocity at the

bright gap is not yet understood the good agreement of spectroscopic results (accounting for diffusion) with canonical evolution makes several non-canonical scenarios discussed in Sect. 2.1 appear unlikely: Helium mixing, rotation and high primordial helium abundance would all increase the luminosities of the hot HB stars (resulting in lower  $\log g$ , but canonical masses, see Crocker et al. 1988; Sweigart 1997a). Currently, however, stars with low  $\log g$  show also low masses (Moehler et al. 2000b), suggesting deficiencies in the analysis rather than non-canonical evolutionary effects as cause. Dynamical interactions are unlikely to produce the tight sequence of stars in the  $T_{\text{eff}}$ ,  $\log g$ -diagram. These statements, however, are currently valid only for those (intermediate metallicity and metal-poor) globular clusters where spectroscopic analyses of blue tail/blue HB stars exist. More spectroscopic analyses, esp. in more metal-rich clusters, would help to verify the suggestion of Piotto et al. (1999) that the faint gap corresponds to a “forbidden” mass (which would result in cooler gap temperatures in more metal-rich globular clusters).

Still unexplained, however, are the low masses found for cool blue HB stars (which are not affected by diffusion) in, e.g., NGC 6397 and M 92. For those stars a longer distance scale to globular clusters would reduce the discrepancies. Such a longer distance scale has been suggested by several authors using HIPPARCOS results for metal-poor field subdwarfs to determine the distances to globular clusters by fitting their main sequence with the local subdwarfs (see Reid 1999, for an overview of the HIPPARCOS results). Carretta et al. (2000) present an extensive and excellent discussion of various globular cluster distance determinations and the zoo of biases that affect them. It is interesting to note that for M 92 and NGC 6397 the new distance moduli are  $0^m3 - 0^m6$  larger than the old ones, thereby greatly reducing the mass discrepancies (see also Heber et al. 1997). The results of spectroscopic analyses of BHB stars (cooler than 11,000 K to 12,000 K) in globular clusters therefore favour the longer distance scale (Moehler 1999)<sup>10</sup>.

<sup>10</sup>de Boer et al. (1997), however, report that HIPPARCOS parallaxes for field HBA stars still yield masses significantly below the canonical mass expected for these objects.

### 3. Horizontal Branch Stars in Metal-Rich Globular Clusters

So far we have dealt with blue HB and blue tail stars in metal-poor ( $[\text{Fe}/\text{H}] < -1$ ) globular clusters. As mentioned in Sect. 1 the HB morphology correlates with metallicity, i.e. HB stars in metal-rich globular clusters will populate mainly the cool regions of the HB because for a given mass of the hydrogen envelope the resulting effective temperature decreases with increasing metallicity. The detection of sdB/sdO candidates in the metal-rich open clusters NGC 188 ( $[\text{Fe}/\text{H}] \approx 0$ ) and NGC 6791 ( $[\text{Fe}/\text{H}] \approx +0.5$ ) by UIT (Landsman et al. 1998) and optical photometry (Kaluzny & Udalski 1992), followed by the spectroscopic verification of sdB stars in NGC 6791 (Liebert et al. 1994) proves, however, that at least extreme HB stars can be produced also in metal-rich systems (see also D’Cruz et al. 1996, for theoretical scenarios).

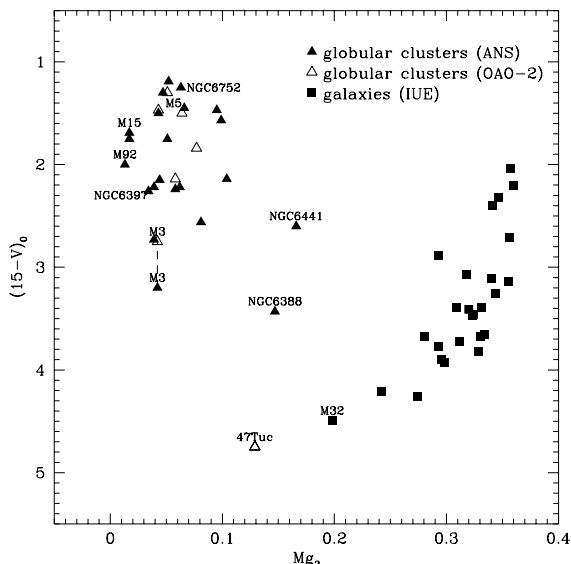


Fig. 3.— UV-visual colour  $(15 - V)_0$  vs. metallicity index  $\text{Mg}_2$  for globular clusters and elliptical galaxies (adapted from Dorman et al. 1995, 15 being the brightness at  $1500 \text{ \AA}$ ). The metal-poor globular clusters discussed in Sect. 2 and the “transition” objects between globular clusters and elliptical galaxies are identified.

UV observations of elliptical galaxies, which are in general even more metal-rich than metal-rich globular clusters (based on the strength of

the  $\text{Mg}_2$  index, cf. Fig. 3) showed that such old, metal-rich systems contain hot stars (Burstein et al. 1988). Stellar evolution models yield the maximum lifetime UV output for EHB stars with envelope masses  $M_{\text{env}} \leq 0.02 M_{\odot}$  (see also Greggio & Renzini 1990, 1999), while post-AGB stars do not live long enough at high temperatures to play a significant rôle for the UV flux. Further evidence in support of hot subdwarfs as cause for the UV excess in elliptical galaxies is provided by Brown et al. (1997): Their analysis of HUT spectra of 6 elliptical and S0 galaxies shows that models with super-solar metal and helium abundances provide the best fit to the flux distribution of the observed spectra and that EHB stars are required in all fits. Most absorption line features (of C, N, Si, i.e. light elements), however, are consistent with  $[\text{M}/\text{H}] = -1$ , in contrast to the energy distribution. This may be due to diffusion in the atmospheres of the EHB stars (see Sect. 2.4).

Dorman et al. (1995) present a thorough discussion of the observational evidence for UV excess in elliptical galaxies and compare the galaxy data to those obtained for globular clusters. Comparing the UV-visual colour  $(15 - V)_0$  for galaxies and globular clusters to the  $\text{Mg}_2$  metallicity index (see Fig. 3, 15 being the observed brightness at  $1500 \text{ \AA}$ ) they find that while the globular clusters and the galaxies occupy distinct ranges in  $\text{Mg}_2$  they overlap in  $(15 - V)_0$  with the globular clusters being bluer on average. The region between globular clusters and galaxies in  $\text{Mg}_2$  is occupied by the metal-rich globular clusters 47 Tuc, NGC 6388, NGC 6441, and the small elliptical galaxy M 32 (see Brown et al. 2000, for far-UV HST observations of this galaxy). The discovery of hot stars in the metal-rich “transition” globular clusters (see Sect. 1) is thus of special interest as analyses of these stars may provide additional information on the nature of the UV excess in elliptical galaxies.

Rich et al. (1993) analysed IUE spectra of the cores of 11 disk globular clusters. The surface light distribution in these spectra becomes more concentrated towards shorter wavelengths for the clusters with the highest UV fluxes. The UV colours of the metal-rich globular clusters NGC 6388, NGC 6441, NGC 6624, NGC 6637 are almost as blue as those of metal-poor globular clusters (see Fig. 3). The IUE observations of NGC 6637 and NGC 6624 could be explained by

one post-EHB star or a few EHB stars, while for NGC 6441, which shows a rise in UV flux towards shorter wavelengths (similar to elliptical galaxies), post-HB stars are the most likely sources. The ratio  $L_{UV}/L_{total}$  of the clusters showing high far-UV fluxes agree very well with those seen in elliptical galaxies, whereas that of NGC 6388, which shows a flat UV spectrum (best explained by blue HB stars), is one order of magnitude lower. 47 Tuc does not show any evidence for stars hotter than blue stragglers within the IUE aperture.

Some years later Rich et al. (1997) discovered the first well populated blue tails in metal-rich globular clusters from WFPC2 photometry of the cores of NGC 6388 and NGC 6441. Most surprisingly, the HB stars at the top of the blue tail are roughly  $0^m.5$  brighter in  $V$  than the red HB “clump,” which is strongly sloped as well. The slight HB tilt ( $\Delta V \approx 0^m.1$ ) expected for metal-rich globular clusters due to the variation in bolometric correction for metal-rich BHB stars (Brocato et al. 1999) is much smaller than the observed slope. Differential reddening alone is probably not the cause of this additional slope (Piotto et al. 1997; Sweigart & Catelan 1998; Layden et al. 1999). WFPC2 photometry of the core of 47 Tuc obtained within the same programme does not show any evidence for a blue HB or a blue tail nor any slope along its red HB. Layden et al. (1999) verify the slope of the blue HB and red clump in NGC 6441 and recent analyses of RR Lyrae variables in NGC 6388 and NGC 6441 (Layden et al. 1999; Pritzl et al. 1999) strongly indicate that the RR Lyrae stars of these globular clusters are substantially brighter than canonical models would predict.

O’Connell et al. (1997) detected about 20 hot stars on the UIT far-UV image of 47 Tuc, which they identify with those producing the UV upturn in elliptical galaxies. Their number, however, is too small to produce a significant UV upturn in 47 Tuc. The much larger field of the UIT accounts for the different results of UIT vs. IUE and WFPC2 observations. The small number of hot stars in 47 Tuc agrees with the result of Rose & Deng (1999) that only about 7% of the mid-UV light of 47 Tuc comes from stars hotter than about 7,500 K (most of which are probably blue stragglers).

Dorman et al. (1997) find evidence for hot stars

in NGC 362 from UIT observations. While this globular cluster is not metal-rich, its HB morphology is too red for its metallicity. Together with NGC 288, which has a predominantly blue HB at a similar metallicity, it forms a second-parameter pair of globular clusters (meaning that an additional parameter besides metallicity is necessary to explain the difference in HB morphology between these two clusters).

What are the possible origins for the hot stars in these four globular clusters?

#### *High mass loss tail:*

Dorman et al. (1997) and O’Connell et al. (1997) suggest that the hot stars in NGC 362 and 47 Tuc are simply the high mass-loss tail of the red HB distribution. A high mass loss tail can most probably not explain the much more numerous blue stars in NGC 6388 and NGC 6441. Moreover, increasing RGB mass loss moves an HB star blueward in the  $V$ ,  $B - V$  plane but does not increase its luminosity (the same holds true for an increase in age).

#### *Dynamical interactions:*

Bailyn (1995) has reviewed the binary evolution scenarios which could yield hot subdwarf stars in globular clusters (see also Sect. 2.1). Binary evolution could be a valid explanation for 47 Tuc and NGC 362 although it is puzzling that the center of 47 Tuc (where interactions should be most pronounced) does not show any evidence for hot stars, whereas the core of NGC 362 shows a concentration of hot stars (Dorman et al. 1997). It is, however, not yet clear whether the hot stars in the core of NGC 362 are HB stars or extreme blue stragglers.

If dynamical interactions created the hot HB stars in NGC 6388 and NGC 6441 these stars should be more centrally concentrated than the RGB stars which is not evident in the HST data. One should note, however, that Layden et al. (1999) find a much less pronounced blue tail in the outer regions of NGC 6441 (where of course the contamination by the field bulge population is much stronger) and suggest that the blue HB/blue tail stars are more centrally concentrated than the red clump stars. However, binaries cannot explain the slope of the HB seen in NGC 6388 and NGC 6441.

#### *Spread in metallicity:*

This scenario was first discussed by Piotto et al. (1997) to explain the sloped HB's found in NGC 6388 and NGC 6441. Model calculations by Sweigart (2001) show that the metal-poor end ( $[\text{Fe}/\text{H}] = -2.3$ ) of the zero-age HB (ZAHB) for these variable metallicity tracks is about  $0^m4$  more luminous at the top of the blue tail than the canonical ZAHB for  $[\text{Fe}/\text{H}] = -0.5$ . In this case NGC 6388 and NGC 6441 might be metal-rich analogues of  $\omega$  Cen, the only other GC known to show a spread in metallicity.

Two of the mechanisms discussed in Sect. 2.1 may also produce hot HB stars and a sloped HB in metal-rich globular clusters: Both *rotation* and *helium mixing* can create brighter and hotter HB stars. Rotation and/or mixing strong enough to produce the observed slope of the HB in NGC 6388 and NGC 6441 would at the same time produce a considerable number of hot stars.

While a high primordial helium abundance can also explain a sloped HB together with a blue tail in a metal-rich globular cluster (Catelan & de Freitas Pacheco 1996; Sweigart & Catelan 1998), this scenario also predicts a much larger value for the number ratio  $R$  ( $= \text{HB}/\text{RGB}$ ) than the value recently obtained by Layden et al. (1999) for NGC 6441.

Moehler et al. (2000c) analysed hot HB star candidates in 47 Tuc and NGC 362: Three of the four blue HB stars analysed in 47 Tuc and three of the eight observed in NGC 362 are probably members of the clusters and their parameters and masses (except for one spectroscopic/photometric binary in 47 Tuc, which cannot be properly analysed) agree very well with canonical evolutionary tracks.

The three spectroscopically verified hot HB stars in 47 Tuc are much hotter ( $10,000 \text{ K} < T_{\text{eff}} < 15,000 \text{ K}$ ) than the rest of the HB population, which is (except for the single RR Lyr V9) entirely redward of the instability strip<sup>11</sup>. The small number of hot HB stars<sup>12</sup> in 47 Tuc, and their high temperatures, point to a scenario in which they

have a different physical origin than the dominant red HB population (e.g. binary interactions, although the lack of central concentration remains a strong caveat for this scenario).

As the separation between the hot and cool HB stars in NGC 362 is much smaller, it is plausible that the blue HB stars arise from a small percentage of red giants with unusually high mass loss. The three probable member stars in NGC 362 are all located within  $2.5$  of the cluster center, while the remaining five stars (probably members of the SMC, for more details see Moehler et al. 2000c) are all more than  $3.5$  from the center. It would be interesting to study the stellar parameters of the hot stars in the core region, where also the relative SMC contamination should be much lower.

The atmospheric parameters derived for the hot HB stars in NGC 6388 and NGC 6441 (Moehler et al. 1999) on the other hand place the studied stars preferentially *below* the canonical ZAHB. The derived gravities for most stars are *significantly* larger than those predicted by the non-canonical tracks (rotation, helium-mixing) that reproduce the upward sloping horizontal branches.

A spread in metallicity, which requires the blue tail stars to be metal-poor, would reduce the discrepancies found by Moehler et al. (1999): The authors relied on the equivalent width of the Ca II K line to place the analysed stars on the hot side of the Balmer maximum. A reduction in metallicity would reduce the expected equivalent width of the Ca II K line also for temperatures below 9,000 K to values consistent with the observed ones (including the high reddening of these clusters). If the cool solutions were chosen all stars except one end up close to the ZAHB computed for varying metallicity and the problem of the high gravities vanishes.

In summary one can state that hot HB stars in metal-rich globular clusters with few such stars (47 Tuc, NGC 362) show parameters in agreement with canonical evolution (i.e. high mass loss tail), although binary evolution may play a rôle. The numerous hot HB stars in NGC 6388 and NGC 6441, however, can currently be best explained by a spread in metallicity, accompanied by canonical evolution.

<sup>11</sup>A fourth probable hot star member of 47 Tuc is UIT-14, which is only  $1.7'$  from the cluster center, and for which the IUE spectrum obtained by O'Connell et al. (1997) indicates  $T_{\text{eff}} \approx 50,000 \text{ K}$ .

<sup>12</sup>Kaluzny et al. (1997) find only 2 candidates for blue tail stars in 47 Tuc (the fainter of which is very similar to the SMC star MJ8279 discussed by Moehler et al. 2000c)

#### 4. UV Bright Stars in Globular Clusters

As mentioned in Sect. 1 UV bright stars have originally been defined as stars brighter than the horizontal branch and bluer than red giants (Zinn et al. 1972, see also Fig. 1), that are brighter in  $U$  than any other cluster star.

Zinn (1974) observed spectra of 38 optically selected UV bright stars in 8 globular clusters. He found that – at a given age and metallicity – different HB morphologies result in different UV bright star populations: The presence/absence of “supra-HB” stars is correlated with the presence/absence of hot HB stars in M 13, M 15, and M 3. This agrees with the theoretical expectation that hot HB stars evolving away from the HB show up as “supra-HB” stars. The more luminous UV bright stars in all three globular clusters are consistent with post-AGB tracks. Also the existence of a planetary nebula and the presence of red HB stars in M 15 (which is unusual for such a metal-poor globular cluster) are linked to each other: The red HB stars in M 15 have masses of  $0.8 - 0.9 M_{\odot}$ , which favour the creation of planetary nebulae (compared to less massive BHB or blue tail stars). Schönberner (1983) discusses the theoretical evolution of post-AGB stars with special emphasis on the production of planetary nebulae: The  $0.546 M_{\odot}$  model, which leaves the AGB before thermal pulses start (post-early AGB), evolves so slowly that its age at 30,000 K (the temperature for planetary nebula ionization) exceeds the age of the oldest known planetary nebulae. Thus the lower mass limit for central stars of planetary nebulae is taken to be  $0.55 M_{\odot}$ .

The search for UV bright stars in globular clusters continued and Harris et al. (1983) list 29 globular clusters with 23 (11) UV bright stars bluer than  $(B - V)_0 = 0$  that are definite (probable) cluster members. de Boer (1985) used IUE spectra of 10 hot UV bright stars in 7 globular clusters to estimate their contribution to the integrated UV light of the respective globular clusters: hot post-AGB stars contribute less than 3% to the total cluster light at  $3300\text{\AA}$ , increasing to about 15% at  $1500\text{\AA}$  and further increasing towards even shorter wavelengths. de Boer (1987) gives a compilation of 45 luminous hot UV bright stars ( $M_V < 0$ ,  $(B - V)_0 < 0.2$ ) in 36 globular clusters.

Hot post-(extreme)HB and post-(early) AGB stars do not necessarily fulfil the original definition of UV bright stars: As stars get hotter the maximum of their flux distribution moves to ever shorter wavelengths and especially the less luminous UV bright stars evolving away from the extreme HB can be quite faint at visual and near-UV wavelengths. The early lists of hot UV bright stars are thus certainly incomplete as they are based on optical searches, which favour luminous hot UV bright stars and are also limited in their spatial coverage due to crowding in the cluster cores. As hot UV bright stars shine up in far-UV images of globular clusters the Ultraviolet Imaging Telescope (UIT, Stecher et al. 1997) was used to obtain ultraviolet ( $\sim 1620\text{\AA}$ ) images of 14 globular clusters. The solar-blind detectors on UIT suppress the cool star population, which allows UV-bright stars to be detected into the cluster cores, and the  $40'$  field of view of UIT is large enough to image the entire population of most of the observed clusters. Thus the UIT images provide a complete census of the hot UV-bright stars in the observed clusters, which is well suited to test post-(extreme)HB and post-(early) AGB evolutionary tracks. Such a test is especially important as hot UV bright stars probably make a significant contribution to the UV-upturn observed in elliptical galaxies (Greggio & Renzini 1990; Dorman et al. 1995; Dorman 1997; Brown et al. 1997; Greggio & Renzini 1999; Brown et al. 2000).

The need for further information on these evolutionary stages is also illustrated by the results of Jacoby et al. (1997) for planetary nebulae in globular clusters. In their O III imaging survey of 133 globular clusters they found only four planetary nebulae, two of which were previously known (Ps1 in M 15 and IRAS 18333-2357 in M 22, cf. Sect. 1). Based on the planetary nebula luminosity function for metal-poor populations they expected to find 16 planetary nebulae in their sample. However, their O III search may have missed some old, faint planetary nebulae. And – even more important – their assumption that all stars in a globular cluster will eventually go through the AGB phase is not valid for globular clusters like NGC 6752, where about 30% of the HB population consist of EHB stars (with  $T_{\text{eff}} > 20,000\text{ K}$ ), which evolve into white dwarfs without ever passing through the thermally pulsing AGB phase. While such

globular clusters are expected to be deficient in post-AGB stars, they should show a substantial population of less luminous ( $1.8 < \log \frac{L}{L_{\odot}} < 3$ ) UV-bright stars, which can be either post-EHB stars or post-early AGB stars, neither of which would produce a planetary nebula.

All this emphasizes the need for spectroscopic analyses of hot UV bright stars to compare their parameters to evolutionary calculations. Most analyses so far, however, have been limited to the use of IUE spectra. While IUE spectra allow a good determination of  $T_{\text{eff}}$  for hot stars they are not very suitable to determine  $\log g$  (see Cacciari et al. 1995). Analyses that also used hydrogen lines (line profile fits or equivalent widths) or the shape of the far-UV continuum were performed for eight optically selected hot UV bright stars (in some cases only the most recent analysis is given): M22 II-81 (Glaspey et al. 1985); NGC6712-C49 (Remillard et al. 1980, only lower limit for  $T_{\text{eff}}$ ); NGC 6397 ROB162 (Heber & Kudritzki 1986); NGC 1851 UV5, M 3 vZ1128 (Dixon et al. 1994); 47 Tuc BS (Dixon et al. 1995); M13 Barnard 29 (Conlon et al. 1994),  $\omega$  Cen ROA5139 (Moehler et al. 1998b). Moehler et al. (1998a, ground-based observations, ten stars) and Landsman et al. (2001, HST observations, three stars) observed and analysed spectra of UV-bright stars identified as such solely on the UIT images. The derived effective temperatures and gravities of all these stars are plotted in Fig. 4, along with evolutionary tracks.

Obviously the dominance of post-AGB stars among optically selected hot UV bright stars is due to heavy bias of the selection towards the most luminous stars. The analysis of optically selected hot UV bright stars thus gives a wrong impression of the importance of the various evolutionary phases that contribute to the UV flux of old stellar populations. The lack of classic post-AGB stars among hot UV bright stars in globular clusters may be understood from the different lifetimes: The lifetime of Schönberner’s post-early AGB track is about 10 times longer than his lowest mass post-AGB track. Thus, even if only a small fraction of stars follow post-early AGB tracks, those stars may be more numerous than true post-AGB stars. Due to their relatively long lifetime, post-early AGB stars are also unlikely to be observed as central stars of planetary nebulae

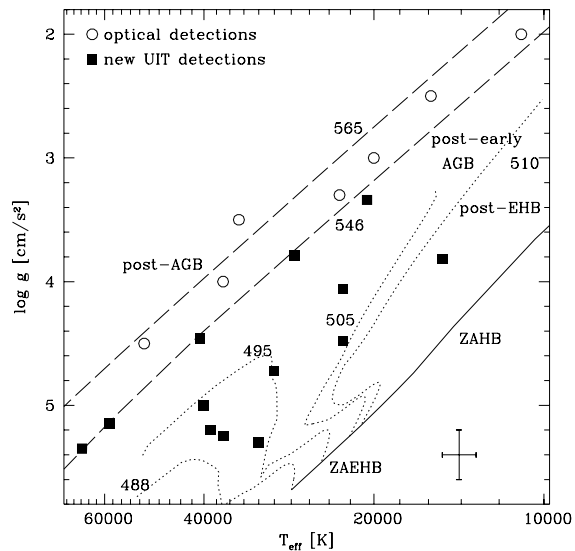


Fig. 4.— The atmospheric parameters of hot UV bright stars compared to evolutionary tracks. The solid and dotted lines mark the ZAHB and post-ZAHB evolutionary tracks for  $[\text{Fe}/\text{H}] = -1.48$  (Dorman et al. 1993). The dashed lines give post-AGB ( $0.565 M_{\odot}$ ) and post-early AGB ( $0.546 M_{\odot}$ ) tracks (Schönberner 1983). All tracks are labeled with the mass of the stars in units of  $10^{-3} M_{\odot}$ . The filled symbols mark UV bright stars identified as such only by UIT, while the open symbols mark UV bright stars already known from optical searches (see text for references).

(see above).

Theoretical simulations would be useful to determine whether the relative populations of post-AGB and post-early AGB stars can be accommodated using existing post-HB evolutionary tracks or if additional process (e.g. additional mass loss) are necessary. Possible discrepancies are indicated by Landsman et al. (1996), who find only 4 post-EHB stars in UIT observations of NGC 6752, whereas 11 would be expected.

## 5. White dwarfs in globular clusters

White dwarfs are the final stage of all low-mass stars (like those discussed so far) and globular clusters should thus contain lots of them. However, these stars managed to evade detection until recently photometric white dwarf sequences were

discovered in four globular clusters by observations with HST (Paresce et al. 1995; Richer et al. 1995, 1997; Cool et al. 1996; Renzini et al. 1996; Zoccali et al. 2001). These sequences not only allow to verify time scales for the evolution of low-mass stars, but also offer an independent way to determine distances to globular clusters, as suggested by Renzini et al. (1996): The basic idea is to fit the white dwarf cooling sequence of a globular cluster to an appropriate empirical cooling sequence of local white dwarfs with well determined trigonometric parallaxes. The procedure is analogous to the classical main sequence fitting but has two main advantages: White dwarfs have – due to diffusion – very simple atmospheres that are either hydrogen-rich (DA) or helium-rich (DB/DO), independent of their original metallicity. Thus one can avoid the problem to find local calibrators with the same metallicities as the globular cluster stars. In addition, white dwarfs are locally much more abundant than metal-poor subdwarfs, thus enlarging the reference sample.

Photometric observations alone, however, are not sufficient to select the appropriate local calibrators: Hydrogen-rich DA’s and helium-rich DB’s can in principle be distinguished by their photometric properties alone in the temperature range  $10,000\text{ K} \leq T_{\text{eff}} \leq 15,000\text{ K}$  (Bergeron et al. 1995a). Renzini et al. (1996) classified two white dwarfs in NGC 6752 as DB’s by this method and Richer et al. (1997) speculate that the brightest white dwarf in M 4 ( $V=22.08$ ) might be a hot (27,000K) DB star. However, without a spectral classification, those stars could also be high-mass DA white dwarfs, possibly a product of merging.

Also, the location of the white dwarf cooling sequence is highly sensitive to the white dwarf mass. Renzini et al. (1996) argued that the white dwarf masses in globular clusters are constrained to the narrow range  $0.51\text{ M}_{\odot} \leq M_{\text{WD}} \leq 0.55\text{ M}_{\odot}$ , but some systematic differences between clusters are obvious: At a given metallicity some globular clusters (e.g. NGC 6752) possess very blue horizontal branches whose low-mass extreme HB stars evolve directly to low mass C/O white dwarfs (bypassing the AGB) and shift the mean white dwarf mass closer to  $0.51\text{ M}_{\odot}$ . Other clusters show only red HB stars, which will evolve to the AGB and form preferably white dwarfs with masses of  $\approx 0.55\text{ M}_{\odot}$ . In addition, low mass white dwarfs ( $M < 0.45\text{ M}_{\odot}$ )

with a degenerate He core (instead of the “normal” C/O core) are produced if the red giant branch evolution is terminated by binary interaction before the helium core exceeds the minimum mass for the onset of helium burning. Recently, Cool et al. (1998) found 3 faint UV-bright stars in NGC 6397 which they suggest could be helium-core white dwarfs (supported by Edmonds et al. 1999). Massive white dwarfs on the other hand may evolve from blue stragglers or result from collisions of white dwarf-binaries with subsequent merging (e.g., Marsh et al. 1995). Salaris et al. (2001) discuss the effects of atmospheric composition and mass on the white dwarf distance determination of globular clusters in more detail.

Due to the faintness of these stars their study by spectroscopic observations is still in its infancy, but first spectroscopic observations of the white dwarf candidates in NGC 6397 (Moehler et al. 2000a), NGC 6752, and M 4 (Moehler et al. 2001) showed that all of them are hydrogen-rich DA white dwarfs. Follow-up spectroscopy at better S/N should allow to derive atmospheric parameters and thereby to verify the distances to these globular clusters.

## 6. Summary

This section provides a brief summary of the most important points discussed in this paper:

- Abundances and rotational velocities of HB stars show a sharp change at temperatures of about 11,000 K to 12,000 K, with the cooler stars displaying the expected cluster abundances and relatively high rotational velocities. The hotter stars show rather low rotational velocities and abundances best explained by diffusion.
- Diffusion, esp. radiative levitation of heavy elements, can most probably solve the problem of the low gravities found previously for HB stars between  $\approx 11,500\text{ K}$  and  $\approx 20,500\text{ K}$ .
- The faint gap along the blue tail at  $M_V \approx 3^m$  separates hot HB from extreme HB stars. The brighter gap at  $M_V \approx 0^m.6$  to  $\approx 1^m.4$  is probably caused by the onset of radiative levitation in the atmospheres of the HB stars. Non-canonical evolutionary scenarios are probably not necessary to explain these



gaps or the results of spectroscopic analyses of hot HB/blue tail stars.

- The physical parameters of cool blue HB stars in metal-poor globular clusters agree with canonical evolutionary tracks, but yield canonical masses preferably for the long distance scale.
- Hot HB stars in metal-rich globular clusters form a rather inhomogeneous group, that cannot be explained by *one* evolutionary scenario.
- Hot UV bright stars selected by far-UV observations show the theoretically expected distribution of evolutionary stages, contrary to optically selected hot UV bright stars, which are biased towards luminous post-AGB stars. The considerable percentage of stars avoiding the thermally pulsing AGB might explain the lack of planetary nebulae in globular clusters.
- White dwarfs in globular clusters so far have been verified to be hydrogen-rich DA white dwarfs.

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